

ENERGY SUPPLY MANAGEMENT METHODS, APPARATUS, MEDIA, SIGNALS AND PROGRAMS

CROSS-REFERENCE TO RELATED APPLICATIONS

- 5 This application claims the benefit of United States provisional patent application serial number **60/457,708**, filed March **27, 2003**, which is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

10 1. Field of Invention

The present invention relates to electrical power supply systems, and more particularly, to methods, apparatus, computer-readable media, signals, and programs for managing energy supplied by an energy supply.

15 2. Description of Related Art

Many applications involve an electrical load, powered by an energy supply. For example, electric automobiles typically include traction motors, powered by various types of batteries. Similarly, a flashlight typically includes a resistor connected to a battery. Thus, referring to Figure 1, an energy supply such as
20 that shown at **20**, is typically connected to a load such as that shown at **22**, for example. For ease of illustration, the load is represented as a resistor, although it will be appreciated that it is not entirely accurate to model some types of loads as resistors.

However, the present inventor has observed that some types of loads
25 connected to energy supplies in the above fashion result in wasted energy. For example, in many cases an electrical load will transfer, dissipate or consume more energy than necessary in order to complete the task that is required of it. In order to generate the energy that is being dissipated or consumed by the load, the energy supply must deplete at least an equivalent

amount of its own potential energy store (in fact, slightly more, due to inefficiencies and imperfections in any system). As a result, the duration of the energy supply is shorter than it would have been, if not for the wasted energy unnecessarily transferred or consumed by the load.

5 SUMMARY OF THE INVENTION

10 The present invention addresses the above shortcoming by providing, in accordance with one aspect of the invention, an apparatus for managing energy supplied by an energy supply. The apparatus includes an energy accumulation device, which in turn includes an energy accumulator and a controller configured to place the energy accumulator in electrical communication with the energy supply and with a load. The apparatus further includes an energy transfer device in communication with the energy accumulation device and with the energy supply and configured to transfer accumulated energy from the energy accumulator to the energy supply.

15 It has been found that the use of such an apparatus to manage the energy supplied by the energy supply in the above manner may serve to significantly reduce the wasted energy unnecessarily transferred or consumed by the load, thereby significantly extending the duration for which the energy supply is able to supply energy to operate the load.

20 The controller may be configured to temporarily place the energy accumulator in electrical communication with the load and the energy supply. For example, the controller may be configured to temporarily interpose the energy accumulator with the load and the energy supply.

25 The energy accumulator may include a capacitor. In such a case, the energy transfer device may be configured to permit discharge of the capacitor into the energy supply.

The energy accumulator may include a first energy accumulator for accumulating energy during a first cycle, and a second energy accumulator

for accumulating energy during a second cycle. The first and second energy accumulators may include first and second capacitors respectively.

In such an embodiment, the energy accumulation device and the energy transfer device may be configured to cooperate to transfer accumulated energy from the second energy accumulator into the energy supply during the first cycle, and to transfer accumulated energy from an energy accumulator of the energy accumulation device other than the second energy accumulator into the energy supply during the second cycle. The energy accumulator other than the second energy accumulator may include the first energy accumulator.

The energy accumulation device may be configured to cooperate to repeatedly execute the first and second cycles in succession.

The controller of the energy accumulation device may be configured to control a switching system to charge the first capacitor and discharge the second capacitor into the energy supply during the first cycle, and to charge the second capacitor and discharge the first capacitor into the energy supply during the second cycle.

In such embodiments, the controller may be configured to maintain a first switch closed while maintaining a second switch open during the first cycle, to place the first capacitor in series with the energy supply and the load while isolating the first capacitor from the energy transfer device. The controller may be configured to maintain a third switch open while maintaining a fourth switch closed during the first cycle, to isolate the second capacitor from the load while placing the second capacitor in communication with the energy transfer device.

The controller may be configured to maintain the first switch open while maintaining the second switch closed during the second cycle, to isolate the first capacitor from the load while placing the first capacitor in communication with the energy transfer device. The controller may also be configured to

maintain the third switch closed while maintaining the fourth switch open during the second cycle, to place the second capacitor in series with the energy supply and the load while isolating the second capacitor from the energy transfer device.

- 5 The controller may be configured to adjust respective durations for which the first switch and the third switch are maintained closed to charge the first and second capacitors respectively, in response to a charge time control signal.

10 If so, the apparatus may further include a charge time control signal generator configured to generate the charge time control signal. For example, such a signal may be generated in response to an adjustable setting of a throttle control. In such an embodiment, the apparatus may further include the throttle control, which in turn may include a variable resistor. The charge time control signal generator may include an analog-to-digital converter configured to generate the charge time control signal in response to a resistance of the
15 variable resistor.

The controller may be configured to adjust respective durations for which the second switch and the fourth switch are maintained closed to discharge the first and second capacitors respectively, in response to a discharge time control signal. If so, the apparatus may further include a discharge time control signal generator configured to generate the discharge time control signal. For example, the discharge time control signal may be generated in response to a voltage of the discharge of the first and second capacitors. The discharge time control signal generator may include an analog-to-digital converter.
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25 The apparatus may further include the switching system, which may include a transistor switching system. Thus, the apparatus may further include the first, second, third and fourth switches, each of which includes a respective transistor. Each of the first, second, third and fourth switches may further include a driver for operating each of the transistors in response to control
30 signals from the controller.

The apparatus may further include the switching system, which alternatively may include a mechanical switching system.

The controller may include a microcontroller.

5 The energy transfer device may include an input port for receiving the accumulated energy from the energy accumulation device in the form of an electrical discharge.

10 The energy transfer device may include a second controller configured to increase an output voltage at an output port of the energy transfer device in communication with the energy supply, to cause the output voltage to tend to a desired voltage exceeding a voltage of the energy supply.

15 The energy transfer device may include an inductor, and wherein the second controller may be configured to increase the output voltage by allowing current to flow from the input port through the inductor until the output voltage may be at least the desired voltage. The energy transfer device may further include a transistor in communication with the inductor, and the second controller may be configured to control the transistor to control the current through the inductor.

20 The energy transfer device may further include an output voltage monitor configured to monitor the output voltage, and the second controller may be configured to control the current through the inductor in response to the output voltage.

The energy transfer device may include an isolator configured to prevent current from flowing from the energy supply into the output port of the energy transfer device. The isolator may include a diode.

25 In accordance with another aspect of the invention, there is provided a method of managing energy supplied by an energy supply. The method includes accumulating energy in an energy accumulator in electrical

communication with the energy supply and with a load, and transferring accumulated energy from the energy accumulator to the energy supply.

Accumulating may include temporarily placing the energy accumulator in electrical communication with the load and the energy supply, which may include temporarily interposing the energy accumulator in series with the load and the energy supply.

Temporarily placing the energy accumulator may include temporarily placing a capacitor in electrical communication with the load and the energy supply to charge the capacitor. Transferring may include discharging the capacitor into the energy supply.

Accumulating may include accumulating energy in a first energy accumulator during a first cycle, and accumulating energy in a second energy accumulator during a second cycle. The first and second energy accumulators may include first and second capacitors respectively. Transferring may include transferring accumulated energy from the second energy accumulator into the energy supply during the first cycle, and transferring accumulated energy from an energy accumulator other than the second energy accumulator into the energy supply during the second cycle. The energy accumulator other than the second energy accumulator may include the first energy accumulator.

Accumulating and transferring may include repeatedly executing the first and second cycles in succession. Executing may include controlling a switching system to charge the first capacitor and discharge the second capacitor into the energy supply during the first cycle, and to charge the second capacitor and discharge the first capacitor into the energy supply during the second cycle. Controlling may include, during the first cycle, maintaining a first switch closed while maintaining a second switch open, to place the first capacitor in series with the energy supply and the load while isolating the first capacitor from an energy transfer device. Controlling may further include, during the first cycle, maintaining a third switch open while maintaining a fourth switch closed, to isolate the second capacitor from the load while placing the second

capacitor in communication with the energy transfer device. Controlling may include, during the second cycle, maintaining the first switch open while maintaining the second switch closed, to isolate the first capacitor from the load while placing the first capacitor in communication with the energy transfer device. Controlling may further include, during the second cycle, maintaining the third switch closed while maintaining the fourth switch open, to place the second capacitor in series with the energy supply and the load while isolating the second capacitor from the energy transfer device.

The method may further include adjusting respective durations for which the first switch and the third switch are maintained closed to charge the first and second capacitors respectively, in response to a charge time control signal. The method may further include generating the charge time control signal, which may be generated in response to an adjustable throttle setting if desired.

The method may further include adjusting respective durations for which the second switch and the fourth switch are maintained closed to discharge the first and second capacitors respectively, in response to a discharge time control signal. The method may further include generating the discharge time control signal, in response to a voltage of the discharge of the first and second capacitors.

Controlling a switching system may include controlling a transistor switching system. In such a case, each of the first, second, third and fourth switches may include a respective transistor, such as a field effect transistor, for example. Alternatively, controlling a switching system may include controlling a mechanical switching system.

Transferring may include receiving the accumulated energy from the energy accumulation device at an input port of an energy transfer device in the form of an electrical discharge.

The method may further include increasing an output voltage at an output port of the energy transfer device in communication with the energy supply, to cause the output voltage to tend to a desired voltage exceeding a voltage of the energy supply. Increasing the output voltage may include allowing current to flow from the input port through an inductor until the output voltage is at least the desired voltage. The method may further include monitoring the output voltage and controlling the current through the inductor in response to the output voltage.

The method may also include preventing current from flowing from the energy supply into the output port of the energy transfer device.

In accordance with another aspect of the invention, there is provided an apparatus for managing energy supplied by an energy supply. The apparatus includes means for accumulating energy, in electrical communication with the energy supply and with a load, and further includes means for transferring accumulated energy from the means for accumulating energy to the energy supply.

The apparatus may further include means for carrying out any of the functions described herein.

In accordance with another aspect of the invention, there is provided a computer-readable medium storing codes for directing a processor circuit to cause the methods described herein to be carried out.

In accordance with another aspect of the invention, there is provided a signal embodied in a communications medium, the signal including code segments for directing a processor circuit to cause the methods described herein to be carried out. In accordance with yet another aspect of the invention, the signal may alternatively be embodied in a carrier wave.

In accordance with another aspect of the invention, there is provided a computer program comprising code means for directing a processor circuit to cause the methods described herein to be carried out.

Other aspects and features of the present invention will become apparent to those ordinarily skilled in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

5 **BRIEF DESCRIPTION OF THE DRAWINGS**

In drawings that illustrate embodiments of the invention,

Figure 1 is a circuit diagram of an energy supply and a load, according to the prior art;

10 Figure 2 is a circuit diagram of an apparatus for managing energy supplied by an energy supply, according to a first embodiment of the invention;

Figure 3 is a circuit diagram of an energy accumulation device of the apparatus shown in Figure 2;

15 Figure 4 is a block diagram of a microcontroller of the energy accumulation device shown in Figure 3;

Figure 5 is a circuit diagram of an energy transfer device of the apparatus shown in Figure 2;

Figure 6 is a block diagram of a microcontroller of the energy transfer device shown in Figure 5;

20 Figure 7 is a flow chart of a parameters routine executed by the microcontroller of the energy accumulation device shown in Figure 4;

25 Figure 8 is a flow chart of an accumulation and transfer routine executed by the microcontroller of the energy accumulation device shown in Figure 4;

Figure 9 is a flow chart of a transfer control routine executed by the microcontroller of the energy transfer device shown in Figure 6;

Figure 10 is a circuit diagram of an apparatus for managing energy supplied by an energy supply, according to a second embodiment of the invention; and

Figure 11 is a circuit diagram of an apparatus for managing energy supplied by an energy supply, according to a third embodiment of the invention.

DETAILED DESCRIPTION

Referring to Figure 2, an apparatus for managing energy supplied by an energy supply according to a first embodiment of the invention is shown generally at 100. In this embodiment, the apparatus 100 includes an energy accumulation device shown generally at 102, including an energy accumulator, and a controller configured to place the energy accumulator in electrical communication with an energy supply 104 and with a load 106. In this embodiment, the apparatus 100 also includes an energy transfer device 108 in communication with the energy accumulation device 102 and with the energy supply 104. The energy transfer device 108 is configured to transfer accumulated energy from the energy accumulator of the energy accumulation device 102 to the energy supply 104.

In this embodiment, for ease of illustration, the load 106 is represented as a simple resistor, although more generally, the load 106 may include other types of loads, including loads that cannot be accurately represented by a simple resistor. For example (without limitation), the load may include an electric motor, if desired.

In the present embodiment, the energy supply 104 has a positive terminal 103 and a negative terminal 105. In general, the energy supply 104 may include any device capable of applying an electromotive force. It will therefore be

understood that the use of the symbol shown in Figure 2 to depict the energy supply is intended to broadly encompass any such source of electromotive force, rather than the narrower alternative meaning sometimes attributed to that symbol (i.e., a single cell electrical energy supply). In this embodiment, the energy supply **104** includes a multi-cell electrical energy supply, which in this embodiment is a **24V** lead-acid battery. Alternatively, however, other types of batteries, or more generally, other suitable types of energy supplies, may be substituted.

ENERGY ACCUMULATION DEVICE

Referring to Figures 2 and 3, the energy accumulation device **102** is shown in greater detail in Figure 3. In this embodiment, the energy accumulation device includes an energy accumulator, or more particularly, includes a first energy accumulator **120** for accumulating energy during a first cycle, and a second energy accumulator **122** for accumulating energy during a second cycle. More particularly, in this embodiment the first and second energy accumulators **120** and **122** include first and second capacitors **124** and **126**, respectively.

More particularly still, in the present embodiment, each of the capacitors **124** and **126** is designed to operate at **25 V**, and has a capacitance of **43,000 μ F**. In this embodiment, the capacitors **124** and **126** were selected for their desired capacitance, as well as their ability to be controlled at a desired switching speed, which in this embodiment is approximately **107 Hz**. In addition, it is desirable for the capacitors to have low internal series resistance (ESR), to facilitate fast charging and discharging with minimal energy loss. In this embodiment, the capacitors **124** and **126** have an internal series resistance of approximately **0.009 Ω** at a temperature of **120°C**. Alternatively, however, other types of capacitors, or more generally, other suitable types of energy accumulators, may be substituted.

In this embodiment, the energy accumulation device **102** includes a controller shown generally at **130**, which is configured to temporarily place each of the

energy accumulators **120** and **122** in electrical communication with the load **106** and the energy supply **104**. More particularly, in this embodiment, the controller **130** is configured to temporarily interpose each of the energy accumulators in series with the load and the energy supply.

5 In this embodiment, the controller **130** includes a microcontroller **132**, or more particularly, a model number **AT90S1200** microcontroller manufactured by Atmel Corporation, having a clock speed of **4 MHz**.

Alternatively, other types of microcontrollers may be substituted. More generally, in this specification, including the claims, the term "controller" is
10 intended to broadly encompass any type of device or combination of devices capable of performing the functions described herein, including (without limitation) other types of microcontrollers, microprocessors, other integrated circuits, other types of circuits or combinations of circuits, logic gates or gate arrays, or programmable devices of any sort, for example, either alone or in
15 combination with other such devices located at the same location or remotely from each other, for example. Additional types of controllers will be apparent to those ordinarily skilled in the art upon review of this specification, and substitution of any such other types of controllers is considered not to depart from the scope of the present invention as defined by the claims appended
20 hereto.

In the present embodiment, the energy accumulation device **102** further includes a switching system shown generally at **140**. In this embodiment, the switching system **140** includes a transistor switching system. More particularly, in the present embodiment, the switching system **140** includes
25 first, second, third and fourth switches, each of which includes a respective transistor. More particularly still, in the present embodiment, the first, second, third and fourth switches respectively include first, second, third and fourth field effect transistors (FETs) **142**, **144**, **146** and **148**. Also in this embodiment, each of the first, second, third and fourth switches includes a
30 corresponding one of a plurality of drivers shown generally at **150**. Each of

the drivers **150** is used to operate its corresponding FET in response to control signals from the controller **130**.

In this embodiment, each of the FETs **142**, **144**, **146** and **148** includes a model IRL **38035** field effect transistor manufactured by International Rectifier Corporation.

In the present embodiment, the FETs were selected for their current-handling ability (in this embodiment, **40** Amps), for their corresponding voltage-handling ability, for their switching speed (in this embodiment, a rise and fall time on the order of **20** nano-seconds), and for their ability to handle high temperatures (in this embodiment, in the range of **150°C**). Alternatively, other types of FETs may be substituted. More generally, other types of switches may be substituted.

Referring to Figures **2** and **3**, in the present embodiment, the switching system **140** includes an input line **152**, which is connected, via an input port **154** of the energy accumulation device **102**, to the load **106**. Also in this embodiment, the switching system **140** includes an output line **156**, which is connected, via an output port **158** of the energy accumulation device **102**, to the energy transfer device **108**.

In this embodiment, the energy accumulation device further includes a charge time control signal generator shown generally at **160**. Generally, in this embodiment, the charge time control signal generator **160** is configured to generate a charge time control signal. More particularly, in this embodiment the charge time control signal generator is configured to generate the charge time control signal in response to an adjustable setting of a throttle control. Alternatively, however, the charge time control signal may be generated in response to other input(s), or may be predefined if desired.

More particularly, in the present embodiment, the throttle control of the charge time control signal generator **160** includes a variable resistor **162**, which in this embodiment is manually controllable by a rotatable switch (not

shown), to allow a user of the apparatus **100** to "throttle" or control the rate at which the apparatus **100** accumulates and transfers energy. In this embodiment, the variable resistor **162** has a maximum resistance of approximately **5 k Ω** , and is manually controllable over a continuous resistance range of approximately **0.5 – 5.0 k Ω** .

In this embodiment, the variable resistor **162** is connected in parallel with a capacitor **164**, which in this embodiment has a capacitance of approximately **3 μ F**.

In the present embodiment, the charge time control signal generator **160** further includes an analog-to-digital (A/D) converter **166**, which is configured to generate the charge time control signal in response to a resistance of the variable resistor **162**. Effectively, the A/D converter **166** acts as a digital ohmmeter to measure the variable resistance of the variable resistor, which in turn is determined by the above-mentioned manual adjustment of the rotatable switch (not shown) by the user. In response to the measured voltage drop across the variable resistor **162**, the charge time control signal generator **160** produces digital signals on signal lines shown generally at **168**, which are connected to signal line input ports of the controller **130**. More particularly, in this embodiment the A/D converter **166** produces digital signals representing the resistance of the resistor **162** as a value between **0** and **255**, with **0** representing the minimum resistance and **255** representing the maximum resistance of the resistor **162**, respectively.

In this embodiment, the energy accumulation device **102** further includes a discharge time control signal generator shown generally at **170**. In this embodiment, the discharge time control signal generator **170** is configured to generate a discharge time control signal, in response to a voltage of the discharge of the first and second capacitors. More particularly, in this embodiment, the discharge time control signal generator **170** includes an operational amplifier **172**. The output line **156** of the switching system **140** is connected through a resistor **174** to the amplifier **172** at a connection point

176, which in turn is connected to a resistor 178 connected to ground. In this embodiment, the resistors 174 and 178 have resistances of 100 k Ω and 50 k Ω , respectively. The operational amplifier 172 produces a signal on a signal line 180, having a voltage proportional to the voltage on the output line 156 of the switching system 140. In this embodiment, the operational amplifier is a model no. PTLC27M7CD operational amplifier manufactured by Texas Instruments Corporation. Alternatively, other types of amplifiers may be substituted.

In this embodiment, the discharge time control signal generator 170 further includes an analog-to-digital (A/D) converter 182, produces digital signals on signal lines 184 in response to the voltage present on the signal line 180, which in turn is proportional to the voltage on the output line 156 of the switching system 140. The signal lines 184 are connected to input ports of the controller 130. The signal lines 184 may be connected to the same input ports as the signal lines 168, provided the controller 130 employs a communications protocol that enables it to differentiate the charge time control signals received from the charge time control signal generator 160, from the discharge time control signals received from the discharge time control signal generator 170. Alternatively, the signal lines 184 may be connected to different input ports than the signal lines 168. In this embodiment, the digital signals produced by the A/D converter 182 represent a value between 0 and 255, corresponding to a minimum and a maximum expected voltage (in this embodiment, 0V and 3V respectively) of the signal received from the operating amplifier 172, which in turn is proportional to the voltage on the output line 156 (which in this embodiment is typically fluctuating up to about 10V).

In the present embodiment, the energy accumulation device 102 further includes a power supply 190. In this embodiment, the power supply 190 includes a first voltage regulator 192, which is in electrical communication with the positive terminal 103 of the energy supply 104 via a power input port 194 of the energy accumulation device 102. The first voltage regulator 192

receives input voltage from the energy supply **104**, in this embodiment at a voltage of approximately **24 V**, and supplies reduced voltages to various components of the energy accumulation device **102**. More particularly, in this embodiment the first voltage regulator **192** provides **12.4 V** to the drivers **150**, the FETs **142**, **144**, **146** and **148**, the A/D converters **166** and **182**, and a second voltage regulator **196**. The second voltage regulator **196** provides **3V** to the controller **130**, and to the throttle control (or more particularly, to the variable resistor **162**) of the charge time control signal generator **160**.

Referring to Figures **2** and **3**, in this embodiment, the negative terminal **105** of the energy supply **104** shown in Figure **2** is used as the ground for the various components of the energy accumulation device **102** shown in Figure **3**. Thus, it will be understood that each of the various connections symbolized as "ground" connections in Figure **3** is in electrical communication with the negative terminal **105** of the energy supply **104**, via a respective one of a plurality of lines **198** shown in Figure **2** (not shown in Figure **3**).

Referring to Figures **3** and **4**, the controller of the energy accumulation device **102** is shown in greater detail at **130** in Figure **4**. As noted above, in this embodiment the controller **130** includes the microcontroller **132**, which in this embodiment has first and second storage devices **220** and **260** respectively. More particularly, in this embodiment the first storage device **220** includes a non-volatile memory, which in this embodiment is a FLASH memory **221**, and the second storage device **260** includes a volatile memory, which in this embodiment is a random access memory (RAM) **261**.

In the present embodiment, the first storage device **220**, or more particularly, the FLASH memory **221**, stores a plurality of routines including instruction codes that program or configure the microcontroller **132** to execute the functionality described herein. More particularly, in this embodiment, the routines stored in the first storage device **220** include an accumulation and transfer routine **222**, and a parameters routine **224**, both of which are described in greater detail below. Effectively, therefore, in this embodiment

the first storage device **220** is a computer-readable medium storing codes for directing a processor circuit (in this embodiment, the microcontroller **132**) to cause the methods described herein to be carried out. However, the first storage device **220** is merely one example of such a computer readable medium. Alternatively, such routines or instruction codes may be provided as software stored on a different medium such as a ROM, an EPROM or an EEPROM, or a compact disc or a floppy diskette, for example, or available from a communications medium such as the Internet, for example. More broadly, any computer-readable medium capable of being used to generate a signal embodied in a communications medium including code segments for directing a processor circuit to cause the methods described herein to be executed may be substituted. More generally, any other suitable medium may be substituted.

In addition to such routines, in the present embodiment, the first storage device **220** also stores various data for use by the microcontroller **132**, and thus includes a default parameters store **240**, a charge parameters look-up table **242**, and a discharge parameters look-up table **244**.

The routines described above configure the microcontroller **132** to define various registers or stores in the second storage device **260**, or more particularly, in the RAM **261**, including a throttle setting register **262**, an output voltage register **264**, a charge parameters store **270**, and a discharge parameters store **280**. The throttle setting register **262** is used to store a value representing a measurement of the throttle control produced by the A/D converter **166** of the charge time control signal generator **160**, and the output voltage register **264** is used to store a value representing a measurement of the voltage on the output line **156** produced by the A/D converter **182** of the discharge time control signal generator **170**.

The charge parameters store **270** is used to define and store a table of charging parameters that the microcontroller **132** uses to control the FETs **142** and **146**, to control the charging of the capacitors **124** and **126**

respectively. In this embodiment, the charge parameters store **270** includes a record for each of the FETs **142** and **146**, and includes a transistor identification field **272**, for identifying the relevant FET (**142** or **146**), and a charge time field **274**, which determines the amount of time in each cycle for which the FET is to be turned on to permit current to flow therethrough, from the input port **154** and the input line **152** into the relevant capacitor **124** or **126**. If desired, the charge parameters store **270** may also include fields for storing further parameters for controlling the FETs **142** and **146** to control the charging of the capacitors **124** and **126**. For example, such additional fields may include a duty cycle field **276** and a duty cycle frequency field **278** for storing a desired duty cycle (e.g. on (x)% of the time, off (100-x)% of the time), and a desired frequency at which the FET switches between the on and off portions of its duty cycle.

Similarly, in this embodiment the discharge parameters store **280** is used to define and store a table of discharging parameters that the microcontroller **132** uses to control the FETs **144** and **148**, to control the discharging of the capacitors **124** and **126** onto the output line **156** of the switching system **140**. In this embodiment, the discharge parameters' store **280** includes a transistor identification field **282**, for identifying the relevant FET (**144** or **148**), and a discharge time field **284**, which determines the amount of time in each cycle for which the FET is to be turned on to permit current to flow therethrough, from the relevant capacitor **124** or **126** onto the output line **156**. If desired, the discharge parameters store **280** may also include fields for storing further parameters for controlling the FETs **144** and **148** to control the discharging of the capacitors **124** and **126**, such as a duty cycle field **286** and a duty cycle frequency field **288** similar to their counterpart fields **276** and **278** described above in connection with the charge parameters store **270**, for example.

As discussed in greater detail below in connection with the parameters routine **224** and the accumulation and transfer routine **222**, generally, the parameters routine **224** continuously executes to cause the microcontroller **132** to generate and store appropriate values in the charge parameters store **270**

and the discharge parameters store **280**, and the accumulation and transfer routine **222** directs the microcontroller **132** to use such parameters to control the charging of the capacitors **124** and **126** and their subsequent discharging to the energy transfer device **108** via the output line **156**.

5 ENERGY TRANSFER DEVICE

Referring to Figures **2** and **5**, the energy transfer device of the present embodiment is shown in greater detail at **108** in Figure **5**. In this embodiment, the energy transfer device **108** includes an input port **300** for receiving accumulated energy from the energy accumulation device **102** in the form of an electrical discharge.

In the present embodiment, the energy transfer device **108** also includes a second controller **302** configured to increase an output voltage at an output port **304** of the energy transfer device in communication with the energy supply **104**, to cause the output voltage at the output port **304** to tend to a desired voltage exceeding a voltage of the energy supply **104**. More particularly, in this embodiment, the input voltage received at the input port **300** is typically fluctuating, up to about **10 V**, and the second controller is configured to increase the output voltage at the output port **304** to cause it to tend to exceed the energy supply voltage, which in this embodiment is **24 V**.

To achieve this, in this embodiment, the energy transfer device **108** includes an inductor **306**, and the second controller **302** is configured to increase the output voltage at the output port **304** by allowing current to flow from the input port **300** through the inductor **306** until the output voltage is at least the desired voltage. In this embodiment, the second controller **302** includes a microcontroller **303** similar to the microcontroller **132** of the energy accumulation device **102**. Also in this embodiment, the inductor **306** is a **40-turn, 30V/40A/1200W** inductor, although alternatively, other inductors may be substituted.

To allow the second controller **302** to control the current flow through the inductor **306**, and hence to control the output voltage, in the present embodiment, the energy transfer device **108** includes a transistor **308** in communication with the inductor **306**, and the second controller **302** is configured to control the transistor **308** to control the current through the inductor **306**. More particularly, in this embodiment the transistor **308** includes a field effect transistor (FET), and the energy transfer device **108** includes a driver **309**, which is used to control the transistor **308** in response to control signals received at the driver **309** from the second controller **302**.

In the present embodiment, the energy transfer device **108** further includes an output voltage monitor **310** configured to monitor the output voltage at the output port **304**, and the second controller **302** is configured to control the current through the inductor **306** in response to the output voltage. More particularly, in this embodiment the output voltage monitor **310** includes a comparator. In this embodiment, the output port **304** is connected through a resistor **314** to the output voltage monitor **310** at a connection point **316**, which in turn is connected through a resistor **318** to ground. In this embodiment, the resistor **314** has a resistance of **190 k Ω** , and the resistor **318** has a resistance of **10 k Ω** . In the present embodiment, the output voltage monitor **310** also receives a reference voltage signal, as discussed in greater detail below. The output voltage monitor **310**, or more particularly, the comparator, effectively divides the voltage detected at the connection point **316**, and compares the divided voltage to the reference voltage, to indirectly determine whether the voltage at the output port **304** exceeds or is less than one or more desired voltage levels.

Alternatively, the output voltage monitor **310** may include an analog-to-digital converter. Alternatively, any other suitable type of voltage monitor may be substituted.

In this embodiment, the energy transfer device **108** also includes an isolator **312** configured to prevent current from flowing from the energy supply **104**

into the output port **304** of the energy transfer device **108**. In the present embodiment, the isolator **312** includes a diode, which effectively permits current to flow in only a single direction. More particularly, the diode has a low minimum forward voltage (i.e., a low minimum voltage that is required to conduct current in the forward direction, such as **0.2V**, for example), but has an extremely high minimum rearward voltage, significantly exceeding that of the energy supply **104**. Alternatively, other types of isolators may be substituted if desired.

In this embodiment, the energy transfer device **108** further includes a first capacitor **320** proximate to the input port **300**, and a second capacitor **322** proximate to the output port **304**. In the present embodiment, the first capacitor **320** has a capacitance of **50 F**, and serves to reduce losses in the inductor **306**. The second capacitor **322** has a smaller capacitance, which in this embodiment is approximately **3300 μ F**.

Referring to Figures **2**, **3** and **5**, in the present embodiment, the energy transfer device **108** further includes a power supply **330**. In this embodiment, the power supply **330** includes a voltage booster **332**, which is in electrical communication with the input port **300** of the energy transfer device **108**. Effectively, therefore, in this embodiment, the various components of the energy transfer device **108** draw their power from the power output of the switching system **140** of the energy accumulation device **102**. The voltage booster **332** serves to boost the voltage received at the input port (typically up to about **10 V**) to a slightly higher voltage of **12.4V**, which it supplies to the driver **309**, and also to a voltage regulator **334**.

The voltage regulator **334** receives the **12.4 V** input, in response to which it outputs **3V** to supply power to the second controller **302**, and also to the output voltage monitor **310**. In this embodiment, in addition to supplying **3V** power to the output voltage monitor, the voltage regulator **334** also effectively supplies the reference voltage signal to the output voltage monitor. In this regard, the **3V** power supply from the voltage regulator **334** is also applied to

first and second resistors **335** and **336** in series, which in this embodiment each have a resistance of **100 kΩ**. A reference signal input port of the output voltage monitor **310** is connected to a point interposed between the resistors **335** and **336**, to receive the reference voltage signal therefrom.

5 Referring to Figures **2** and **5**, in this embodiment, the negative terminal **105** of the energy supply **104** shown in Figure **2** is used as the ground for the various components of the energy transfer device **108** shown in Figure **5**. Thus, it will be understood that each of the various connections symbolized as "ground" connections in Figure **5** is in electrical communication with the negative
10 terminal **105** of the energy supply **104**, via a respective one of a plurality of lines **338** shown in Figure **2** (not shown in Figure **5**).

Referring to Figures **5** and **6**, the second controller of the energy transfer device **108** is shown in greater detail at **302** in Figure **6**. As noted above, in this embodiment the second controller **302** includes the microcontroller **303**,
15 which in this embodiment has first and second storage devices **340** and **360** respectively. More particularly, in this embodiment the first storage device **340** includes a non-volatile memory, which in this embodiment is a FLASH memory **341**, and the second storage device **360** includes a volatile memory, which in this embodiment is a random access memory (RAM) **361**.

20 In the present embodiment, the first storage device **340**, or more particularly, the FLASH memory **341**, is used to store routines including instruction codes that program or configure the microcontroller **303** to execute the functionality described herein. More particularly, in this embodiment, the FLASH memory **341** stores a transfer control routine **342**, described in greater detail below.
25 Effectively, therefore, in this embodiment the first storage device **340** is an example of a computer-readable medium storing codes for directing a processor circuit (in this embodiment, the microcontroller **303**) to cause the methods described herein to be carried out.

In addition, in this embodiment, the first storage device **340** also stores
30 various data for use by the microcontroller **303**, and thus includes a transfer

control parameters store **344** for storing sets of selectable transfer control parameters for use by the microcontroller **303** in controlling the transistor **308** to effectively control the output voltage at the output port **304**, as described in greater detail below.

5 The transfer control routine **342** configures or programs the microcontroller **303** to define various registers or stores in the second storage device **360**, or more particularly, in the RAM **361**, including an output voltage register **362** and a transfer control parameters store **370**. The output voltage register **362** is used to store a value representing a measurement of the output voltage at
10 the output port **304**, produced by the output voltage monitor **310**.

The transfer control parameters store **370** is used to define and store a table of control parameters that the microcontroller **303** uses to control the transistor **308**, in order to effectively control the current through the inductor **306**, and hence to control the output voltage at the output port **304**. More
15 particularly, in this embodiment, in which the transistor **308** is a FET, the transfer control parameters store **370** includes a duty cycle field **372** and a duty cycle frequency field **374** for storing a desired duty cycle (e.g. on (x)% of the time, off (100-x)% of the time), and a desired frequency at which the FET switches between the on and off portions of its duty cycle.

20 OPERATION

PARAMETERS ROUTINE

Referring to Figures 2, 3, 4 and 7, the parameters routine executed by the microcontroller **132** of the energy accumulation device **102** is shown generally at **224** in Figure 7. Generally, in this embodiment, the parameters routine **224**
25 configures the controller **130**, or more particularly, programs the microcontroller **132**, to define charging and discharging parameters and to store such parameters in the charge parameters store **270** and the discharge parameters store **280**, for use by the microcontroller **132** in controlling

charging and discharging of the first and second energy accumulators **120** and **122**.

The parameters routine **224** begins with a first block **400** of instruction codes, which directs the microcontroller **132** to set the contents of the various fields of the charge parameters store **270** and the discharge parameters store **280** in the RAM **261** equal to the contents of the default parameters store **240** in the FLASH memory **221**. In this embodiment, the contents of the charge time fields **274** and discharge time fields **284** for each such record are initially set to zero. The default duty cycle and duty cycle frequency fields may be set to any suitable default values (in this embodiment, the default duty cycle is **50%** on, **50%** off, and the duty cycle frequency is equal to the clock frequency of the microcontroller **132**, which in this embodiment is **4 MHz**).

Block **410** then directs the microcontroller **132** to receive a charge time control signal and a discharge time signal. More particularly, to receive the charge time signal, block **410** directs the microcontroller **132** to receive digital signals from the A/D converter **166** of the charge time control signal generator **160**, representing the variable resistance of the variable resistor **162**, which in turn is determined by a manually adjusted setting by a user of a rotatable switch (not shown). As noted above, the digital signals received from the A/D converter **166** represent a value between **0** and **255**, proportional to the measured resistance of the variable resistor **162**. Block **410** directs the microcontroller **132** to store this received value in the throttle setting register **262** in the RAM **261**.

In this embodiment, to receive the discharge time control signal, block **410** directs the microcontroller **132** to receive digital signals from the A/D converter **182** of the discharge time control signal generator **170**, representing a digital value between **0** and **255**, which in turn is proportional to the voltage on the output line **156**. Block **410** directs the microcontroller to store this received discharge time control value in the output voltage register **264** in the RAM **261**.

Block 420 then directs the microcontroller 132 to adjust respective durations for which the first switch and the third switch (in this embodiment, the FET 142 and the FET 146 respectively) are maintained closed to charge the first and second capacitors 124 and 126 respectively, in response to the charge time control signal received above at block 410. More particularly, in this embodiment, block 420 directs the microcontroller to copy the contents of the throttle setting register 262 into the charge time field 274 of the record in the charge parameters store 270 for each of the FETs 142 and 144. Thus, as the value stored in the throttle setting register 262 is a value between 0 and 255, the charge time field 274 contents are also values between 0 and 255. As will be evident from the description below of the accumulation and transfer routine 222, the microcontroller 132 interprets the charge time value between 0 and 255 as a (1/256) fraction of a pre-defined maximum charge time interval, which in this embodiment is 10 milliseconds.

Thus, in this embodiment, the charge time field 274 contents are the same for both the FET 142 and the FET 146, although alternatively, different charge times may be set if desired. As a further alternative, if desired, rather than setting the charge time values equal to the throttle setting value, different charge time values may be obtained by reference to the charge parameters look-up table 242.

Block 430 then configures the controller 130 to adjust respective durations for which the second switch and the fourth switch (in this embodiment, the FET 144 and the FET 148 respectively) are maintained closed to discharge the first and second capacitors 124 and 126 respectively, in response to the discharge time control signal received above at block 410. To achieve this, in the present embodiment, block 430 directs the processor circuit to set the duration for the second switch (which in this embodiment is the FET 144) as follows:

$$T_{\text{DISCHARGE}} = T_{\text{CHARGE}} - (V_{\text{DESIRED}} - V_{\text{OUTPUT}}) = T_{\text{CHARGE}} - V_{\text{DESIRED}} + V_{\text{OUTPUT}}$$

wherein:

$T_{\text{DISCHARGE}}$ is a value representing the discharge time for the FET **144**, in units of $1/256^{\text{th}}$ of a duration of a cycle;

T_{CHARGE} is the charge time value stored in the charge time field **274** of the record in the charge parameters store **270** corresponding to the first switch (which in this embodiment is the FET **142**);

V_{OUTPUT} is the output voltage value stored in the output voltage register **264**; and

V_{DESIRED} is a predetermined value between **0** and **255** representing a desired output voltage level (in this embodiment, $V_{\text{DESIRED}}=130$).

For faster operation, if desired, the above value $T_{\text{DISCHARGE}}$ may be obtained by reference to the discharge parameters look-up table **244**, rather than by directly calculating the above value.

Block **430** directs the microcontroller **132** to store the above value $T_{\text{DISCHARGE}}$ in the discharge time field **284** of the record in the discharge parameters store **280** corresponding to the FET **144**. In the present embodiment, the discharge times for the second switch (in this embodiment, the FET **144**) and the fourth switch (in this embodiment, the FET **148**) are the same, and thus, in the present embodiment, block **430** also directs the microcontroller **132** to store this value in the discharge time field **284** of the discharge parameters store record corresponding to the FET **148**. Alternatively, if desired, the discharge time value for the FET **148** may be calculated separately using the above relationship, substituting the value T_{CHARGE} for the FET **146** rather than the value T_{CHARGE} for the FET **142**.

Following execution of block **430**, the microcontroller **132** is directed back to block **410**, to re-measure the throttle setting and output voltage as described above, and to continue adjusting the charge and discharge parameters as described above in connection with blocks **420** and **430**.

Alternatively, if desired, the parameters routine **224** may also direct the microcontroller **132** to adjust other charge and discharge parameters, such as the duty cycle and duty cycle frequency for each of the FETs **142**, **144**, **146** and **148**, for example.

5 ACCUMULATION AND TRANSFER ROUTINE

Referring to Figures **2**, **3**, **4**, **7** and **8**, the accumulation and transfer routine is shown in greater detail at **222** in Figure **8**. In this embodiment, the parameters routine **224** shown in Figure **7** and the accumulation and transfer routine **222** shown in Figure **8** are concurrently executed threads.
10 Alternatively, these routines may be executed in alternating fashion or in another suitable temporal relationship, if desired.

Generally, the accumulation and transfer routine **222** configures or programs the controller **130** of the energy accumulation device **102** to repeatedly execute a plurality of cycles in succession, to accumulate energy in the
15 energy accumulators, and to transfer such accumulated energy to the energy transfer device **108**. More particularly, the accumulation and transfer routine configures the microcontroller **132** to cooperate with the energy transfer device **108**, to transfer accumulated energy from the second energy accumulator **122** into the energy supply **104** during a first cycle, and to
20 transfer accumulated energy from an energy accumulator of the energy accumulation device **102** other than the second energy accumulator **122** into the energy supply during a second cycle. More particularly still, in the present embodiment there are two such cycles which the microcontroller **132** is configured to repeatedly execute in succession, and there are two energy
25 accumulators, namely, the first and second energy accumulators **120** and **122**. Thus, in the present embodiment, the energy accumulator other than the second energy accumulator (from which energy is transferred during the second cycle) is the first energy accumulator **120**. Alternatively, however, if desired, a different number of cycles and a different (not necessarily the
30 same) number of energy accumulators may be substituted. For example, a

set of three cycles may be repeated in succession, and a third energy accumulator may be provided.

In this embodiment, the accumulation and transfer routine **222** begins with a first block **510** of codes, which directs the microcontroller **132** to read the contents of the throttle setting register **262** (discussed above in connection with block **410** of the parameters routine **224**), and to determine whether the throttle setting value stored therein is greater than a minimum throttle value (in this embodiment, zero). If it is not, the microcontroller **132** is directed to wait at block **510** until the throttle setting value is greater than the minimum value, indicating user actuation of the throttle.

If at block **510** the throttle setting value is greater than the minimum throttle value, block **520** configures the controller **130** of the energy accumulation device **102** to execute the first cycle, or more particularly, to control the switching system **140** to charge the first capacitor **124** and discharge the second capacitor **126** into the energy supply **104** during the first cycle. (If desired, the discharge of the second capacitor may be omitted for the first execution of the first cycle, as the second capacitor will not have yet acquired a charge; accordingly, the second capacitor may be discharged only during the second and subsequent executions of the first cycle, if desired.)

To achieve this, in this embodiment, block **520** configures the controller **130** to maintain the first switch closed while maintaining the second switch open during the first cycle, to place the first capacitor **124** in series with the energy supply **104** and the load **106** while isolating the first capacitor **124** from the energy transfer device **108**. Block **520** also configures the controller **130** to maintain the third switch open while maintaining the fourth switch closed during the first cycle, to isolate the second capacitor **126** from the load **106** while placing the second capacitor **126** in communication with the energy transfer device **108**.

More particularly, block **520** first directs the microcontroller to maintain the second switch and the third switch open, by maintaining the FETs **144** and

146 respectively in their "off" (non-conducting) states, to prevent discharge of the first capacitor 124 onto the output line 156 and to prevent charging of the second capacitor 126 from the input line 152, respectively. The FETs 144 and 146 will already be in their "off" states each time block 520 is executed to implement the first cycle, as the microcontroller 132 will have been directed to switch the FETs 144 and 146 off at the end of block 530, discussed below.

Block 520 then directs the microcontroller 132 to close the first and fourth switches, by turning the FETs 142 and 148 on, to allow the first capacitor 124 to accumulate charge from the input line 152 in communication with the load 106, and to allow the second capacitor 126 to discharge onto the output line 156 in communication with the energy transfer device 108, respectively. More particularly, block 520 directs the microcontroller 132 to maintain the FET 142 in its "on" (conducting) state for a time interval specified by the contents of the charge time field 274 of the record in the charge parameters store 270 corresponding to the FET 142. During such "on" time, the FET 142 is operated at a duty cycle and duty cycle frequency specified by the contents of the duty cycle field 276 and duty cycle frequency field 278 of the corresponding charge parameters store record. As soon as the specified charge time has elapsed, block 520 directs the microcontroller to open the first switch, by switching the FET 142 to its "off" (non-conducting) state. Similarly, block 520 directs the microcontroller 132 to maintain the FET 148 in its "on" (conducting) state for a time interval specified by the contents of the discharge time field 284 of the record in the discharge parameters store 280 corresponding to the FET 148, during which time the FET 148 is operated at the duty cycle and frequency specified by the corresponding fields 286 and 288 of the discharge parameters store record. As soon as the specified discharge time has elapsed, block 520 directs the microcontroller to open the fourth switch, by switching the FET 148 to its "off" (non-conducting) state.

Following execution of the first cycle at block 520 above, block 530 configures the controller 130 of the energy accumulation device 102 to execute the second cycle, or more particularly, to control the switching system 140 to

charge the second capacitor **126** and discharge the first capacitor **124** into the energy supply **104** during the second cycle.

To achieve this, in this embodiment, block **530** configures the controller **130** to maintain the first switch open while maintaining the second switch closed during the second cycle, to isolate the first capacitor **124** from the load **106** while placing the first capacitor **124** in communication with the energy transfer device **108**. Block **530** also configures the controller **130** to maintain the third switch closed while maintaining the fourth switch open during the second cycle, to place the second capacitor **126** in series with the energy supply **104** and the load **106** while isolating the second capacitor **126** from the energy transfer device **108**.

More particularly, block **530** first directs the microcontroller to maintain the first switch and the fourth switch open, by maintaining the FETs **142** and **148** respectively in their "off" (non-conducting) states, to prevent charging of the first capacitor **124** from the input line **152**, and to prevent discharge of the second capacitor **126** onto the output line **156**, respectively. The FETs **142** and **148** will already be in their "off" states each time block **530** is executed to implement the second cycle, as the microcontroller **132** will have been directed to switch the FETs **142** and **148** off at the end of block **520**, when the specified charge time and discharge time have elapsed, as discussed above.

Block **530** then directs the microcontroller **132** to close the second and third switches, by turning the FETs **144** and **146** on, to allow the first capacitor **124** to discharge onto the output line **156** in communication with the energy transfer device **108**, and to allow the second capacitor **126** to accumulate charge from the input line **152** in communication with the load **106**, respectively. More particularly, block **530** directs the microcontroller **132** to maintain the FET **146** in its "on" (conducting) state for a time interval specified by the contents of the charge time field **274** of the record in the charge parameters store **270** corresponding to the FET **146**. During such "on" time, the FET **146** is operated at a duty cycle and duty cycle frequency specified by

the contents of the duty cycle field **276** and duty cycle frequency field **278** of the corresponding charge parameters store record. As soon as the specified charge time has elapsed, block **530** directs the microcontroller to open the third switch, by switching the FET **146** to its "off" (non-conducting) state.

5 Similarly, block **530** directs the microcontroller **132** to maintain the FET **144** in its "on" (conducting) state for a time interval specified by the contents of the discharge time field **284** of the record in the discharge parameters store **280** corresponding to the FET **144**, during which time the FET **144** is operated at the duty cycle and frequency specified by the corresponding fields **286** and

10 **288** of the corresponding discharge parameters store record. As soon as the specified discharge time has elapsed, block **530** directs the microcontroller to open the second switch, by switching the FET **144** to its "off" (non-conducting) state.

Following completion of the second cycle at block **530**, the controller **130** is

15 directed back to blocks **510** through **530**, to continue repeatedly executing the first and second cycles in succession, as long as the throttle setting detected at block **510** remains above the minimum throttle value.

TRANSFER CONTROL ROUTINE

Referring to Figures **2**, **5**, **6** and **9**, the transfer control routine is shown in

20 greater detail at **342** in Figure **9**. Generally, the transfer control routine **342** configures the controller **302** of the energy transfer device **108** to permit discharge of the capacitors **124** and **126** into the energy supply **104**.

As discussed above in greater detail in connection with the energy transfer device **108** shown in Figure **5**, the voltage received at the input port **300** of the

25 energy transfer device **108** resulting from the discharge of the capacitors **124** and **126** is typically up to about **10 V** in the present embodiment, but is boosted to a desired voltage exceeding the voltage of the energy supply **104** (in this embodiment **24 V**), in order to effectively allow the capacitors **124** and **126** to discharge through the energy transfer device **108** into the energy

30 supply **104** via the output port **304**. In this regard, it has been found that the

apparatus **100** functions more effectively if the voltage at the input port **300** is considerably lower than the desired voltage at the output port **304**, and may be even more effective if the input voltage is lower still, on the order of about 1 V, for example. However, desired voltage relationships will vary with the requirements of a particular embodiment. In this embodiment, also as noted above, this voltage boost is achieved by turning the transistor **308** to its "on" (conducting) state, thereby permitting current to flow through the inductor **306** to ground. In the present embodiment, the transfer control routine **342** controls the manner in which the transistor **308** is actuated, to achieve the desired control of the output voltage at the output port **304** of the energy transfer device **108**.

In this embodiment, the transfer control routine **342** begins with a first block **600** of codes, which directs the microcontroller **303** to operate the transistor **308** to its "on" (conducting) state, with a first set of transfer control parameters. More particularly, in this embodiment the first set of transfer control parameters includes a first duty cycle, and a first duty cycle frequency at which the FET cycles on/off while nominally in the "on" conducting state. More particularly still, in this embodiment the first duty cycle is 50% on / 50% off, and the first duty cycle frequency is 70 Hz.

Block **610** then directs the microcontroller **303** to receive an output voltage value from the output voltage monitor **310**, representing the output voltage at the output port **304** of the energy transfer device **108**, and to compare the detected output voltage value to a pre-determined high threshold value, which in this embodiment is 30V. If the output voltage does not exceed the high threshold value, the microcontroller **303** is directed to continue operating the transistor **308** with the first set of transfer control parameters and to continue monitoring the output voltage at block **610**, until the output voltage does exceed the high threshold value.

If at block **610** the output voltage exceeds the high threshold value, block **620** directs the microcontroller to switch the transistor **308** to a second set of

transfer control parameters. In this embodiment the second set of transfer control parameters includes a second duty cycle and a second duty cycle frequency. More particularly, in this embodiment the second duty cycle is 50% on / 50% off (the same as the first duty cycle value), but the second duty cycle frequency is 60 Hz, slightly less than the first duty cycle frequency. When the transistor 308 is operated at this lower frequency, the current through the inductor 306, and hence the voltage boost that it produces, tends to drop.

Block 630 then directs the microcontroller 303 to receive an output voltage value from the output voltage monitor 310, representing the output voltage at the output port 304 of the energy transfer device 108, and to compare the detected output voltage value to a pre-determined low threshold value, which in this embodiment is 28V. If the output voltage is greater than or equal to the low threshold value, the microcontroller 303 is directed to continue operating the transistor 308 with the second set of transfer control parameters and to continue monitoring the output voltage at block 630, until the output voltage is less than the low threshold value.

If at block 630 the output voltage is less than the low threshold value, the microcontroller is directed back to block 600, to switch the transistor 308 to the first set of transfer control parameters, thereby causing the output voltage to tend to increase.

In practice, in the present embodiment, the presence of the energy supply 104 and the load 106 tend to oppose the increase in voltage produced by the inductor 306, and tend to reduce the output voltage toward the voltage of the energy supply 104. Thus, in this embodiment the transistor 308 is typically operated with the first set of transfer control parameters most of the time.

ALTERNATIVES

Referring to Figures 10, an apparatus according to a second embodiment of the invention is shown generally at 1000 in Figure 10. In this embodiment, the

apparatus **1000** includes a mechanical energy accumulation device **1002**, including a mechanical switching system shown generally at **1004**. First and second mechanical switches **1006** and **1008** are controlled by a switch control **1010**, to alternate between a first cycle in which energy is accumulated in the first capacitor **124** while accumulated energy in the second capacitor **126** is transferred to an energy transfer device **1012** and subsequently into the energy supply **104**, and a second cycle in which energy is accumulated in the second capacitor **126** while accumulated energy in the first capacitor **124** is transferred to the energy transfer device **1012** and subsequently into the energy supply **104**. If desired, the energy transfer device **1012** may also be modified, to include mechanically-switched control of the output voltage boost, rather than transistor-controlled voltage boost as described earlier herein.

Although such mechanical embodiments of the invention may be advantageous in some senses, such as simplicity of design, they also tend to suffer from disadvantages, such as greater energy loss and cumbersome size, as compared to embodiments employing transistor-controlled or other solid state switching systems.

Although the exemplary embodiments described above involve an energy supply operable to supply direct current (DC) power, alternatively, embodiments of the invention may be applied in alternating current (AC) system. For example, referring to Figure **11**, an apparatus according to a third embodiment of the invention is shown generally at **1100**. In this embodiment, an energy supply **1102** includes an alternating current (AC) energy supply. A bridge rectifier shown generally at **1104** serves to convert AC power from the energy supply **1102** into direct current (DC) power, which is applied to the load **106** as described above. If desired, the bridge rectifier **1104** may also include a transformer (not shown) and an RC or LC filter (not shown), as is known in the art, to smooth out the voltage produced by the bridge rectifier. Effectively, therefore, the AC energy supply is converted to a DC energy supply **1106**. If desired, the effective DC energy supply **1106** may include a capacitor or capacitor bank (not shown). A control system **1108**,

which in this embodiment effectively includes both an energy accumulation device and an energy transfer device, includes first and second energy accumulators **1110** and **1112**, which in this embodiment include respective capacitors. A controller **1114** controls the energy accumulators in a manner similar to that described above in connection with the previous embodiments, to accumulate energy, and to transfer the accumulated energy to the AC/DC energy supply in a manner similar to that described above.

More generally, while specific embodiments of the invention have been described and illustrated, such embodiments should be considered illustrative of the invention only and not as limiting the invention as construed in accordance with the accompanying claims.